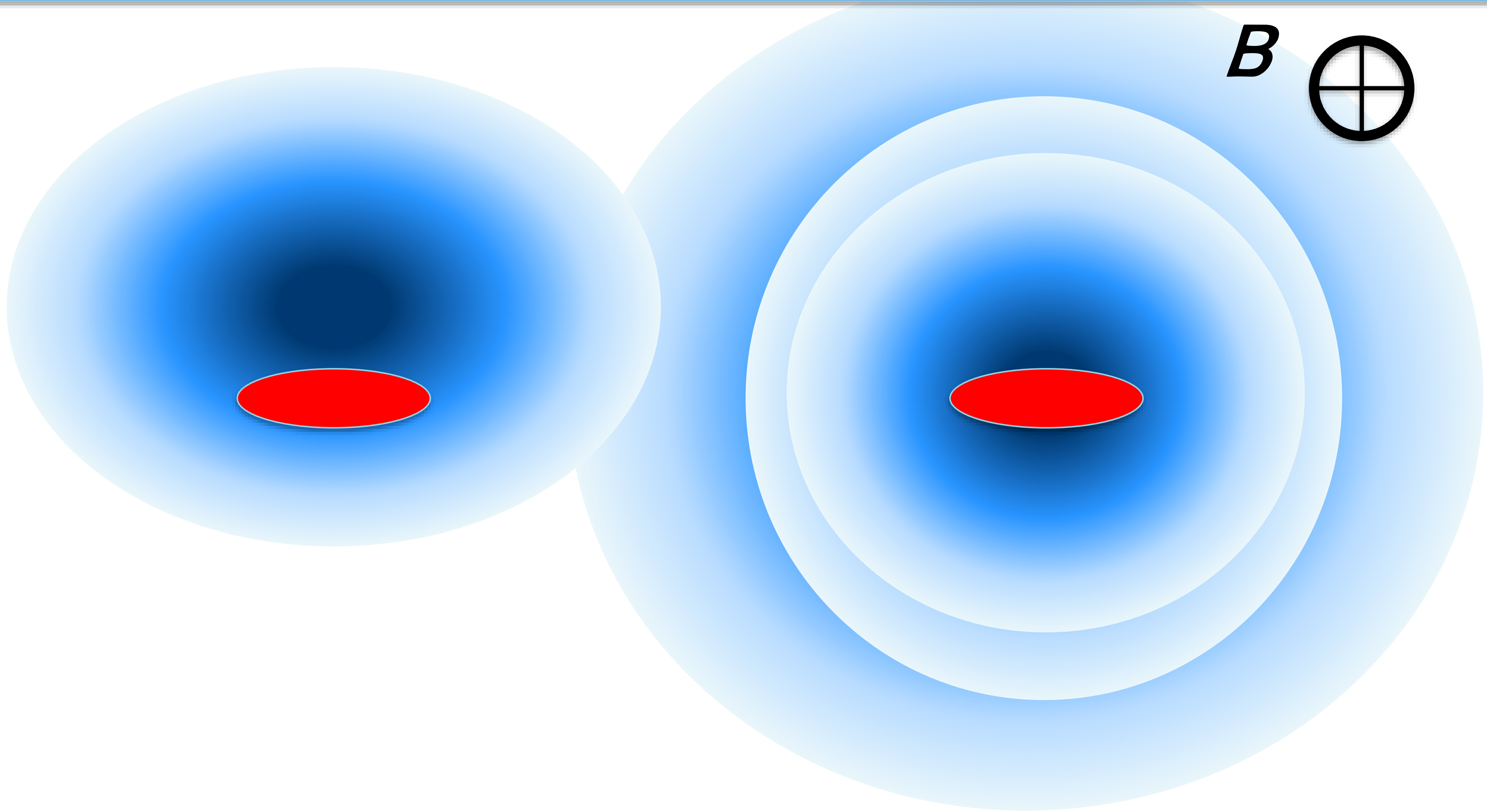
GARD ABP Roadmap Workshop #1
LBNL, December 8-9, 2019

Electron Lenses for:
a) Space-charge compensation
b) Landau damping
c) Halo collimation
d) Beam-beam compensation

V.Shiltsev
with input from G.Stancari, E.Stern, A.Burov, A.Valishev and Yu.Alexahin

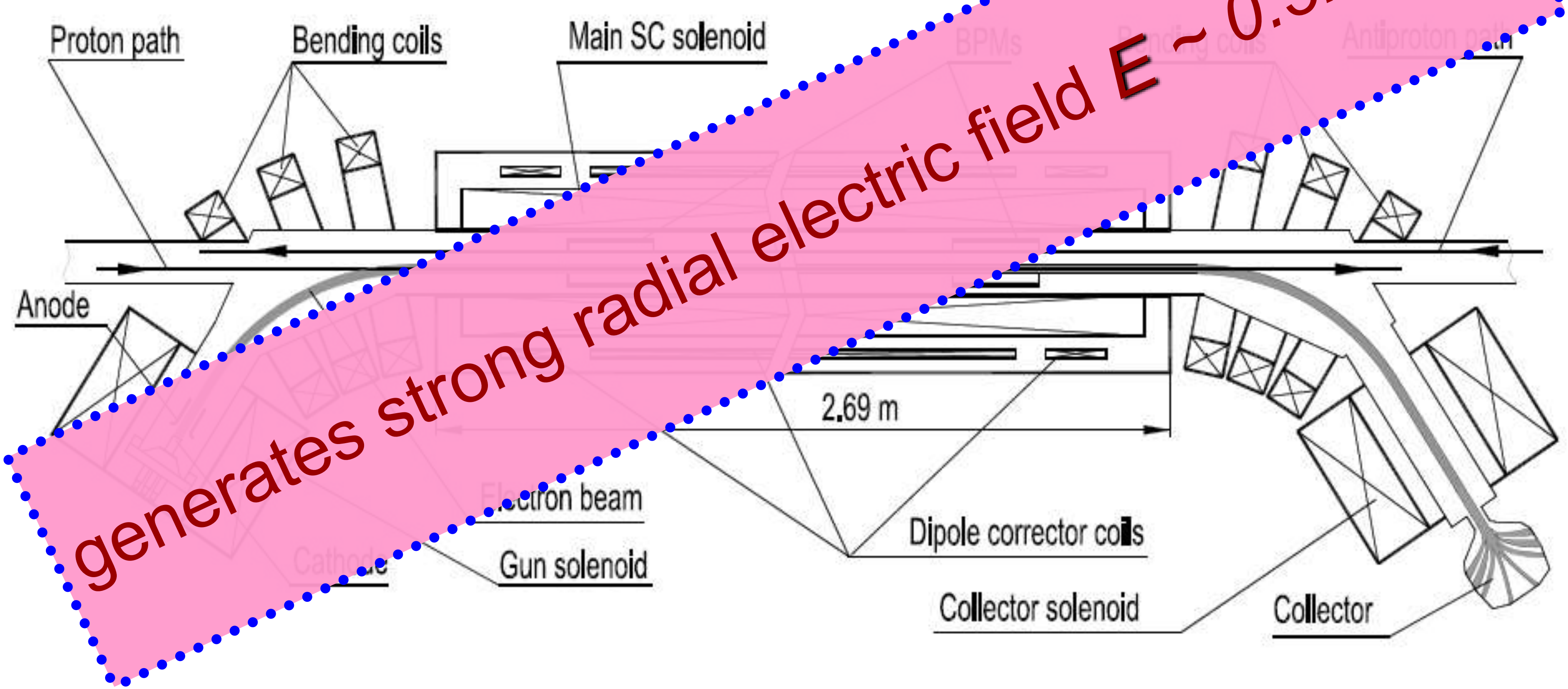
Electron Lens Space Charge – Physics Motivation



Electron Lenses – Since 1997

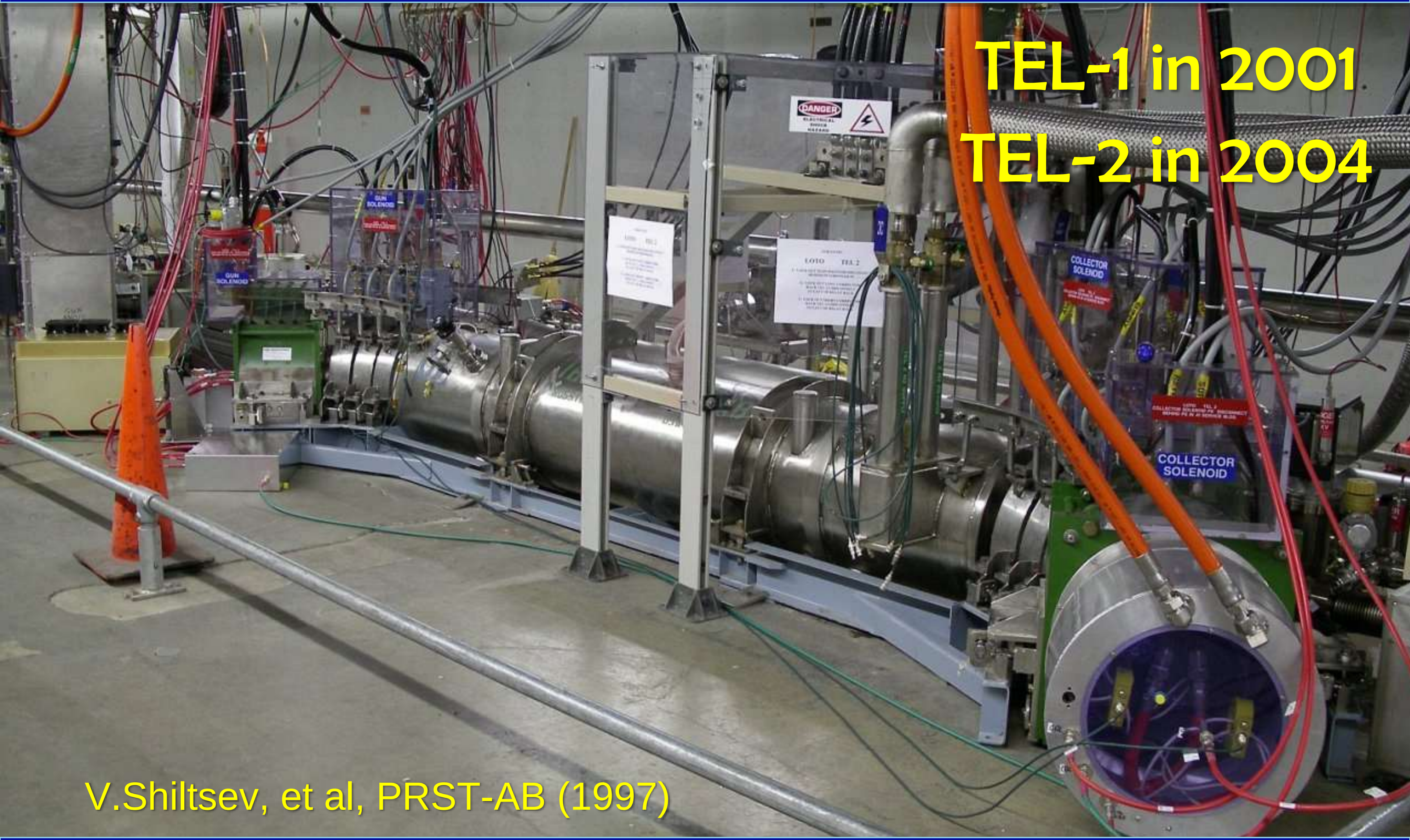
~4 mm dia 2 m long in 3T solenoid beam of ~10kV

~1A electrons (~10^{12}) can turn on/off in ~0.5 usec



generates strong radial electric field *E* ~ 0.3MV/m

Two Electron Lenses Installed in Tevatron



What Electron Lenses Are Good For (1)

In the Fermilab Tevatron Collider:

PAST

- **long-range beam-beam** compensation (varied tune shift of individual 1 TeV bunches by 0.003-0.01);

  *Shiltsev et al., Phys. Rev. Lett. **99**, 244801 (2007)*
- **abort gap collimation** (for years in regular operation);

  *Zhang et al., Phys. Rev. ST Accel. Beams **11**, 051002 (2008)*
- studies of **head-on beam-beam** compensation;

  Shiltsev et al, NJP (2008); Stancari et al., PRL 107, 084802 (2011)
- demonstration of **halo scraping with hollow electron beams**;

  Shiltsev (2006); Stancari et al., Phys. Rev. Lett. 107, 084802 (2011)

What Electron Lenses Are Good For (2)

Presently used in RHIC at BNL for **head-on beam-beam compensation** with significant luminosity gain ~x2

Fischer et al., Phys. Rev. Lett. 115, 264801 (2015)

PRESENT

Current areas of research:

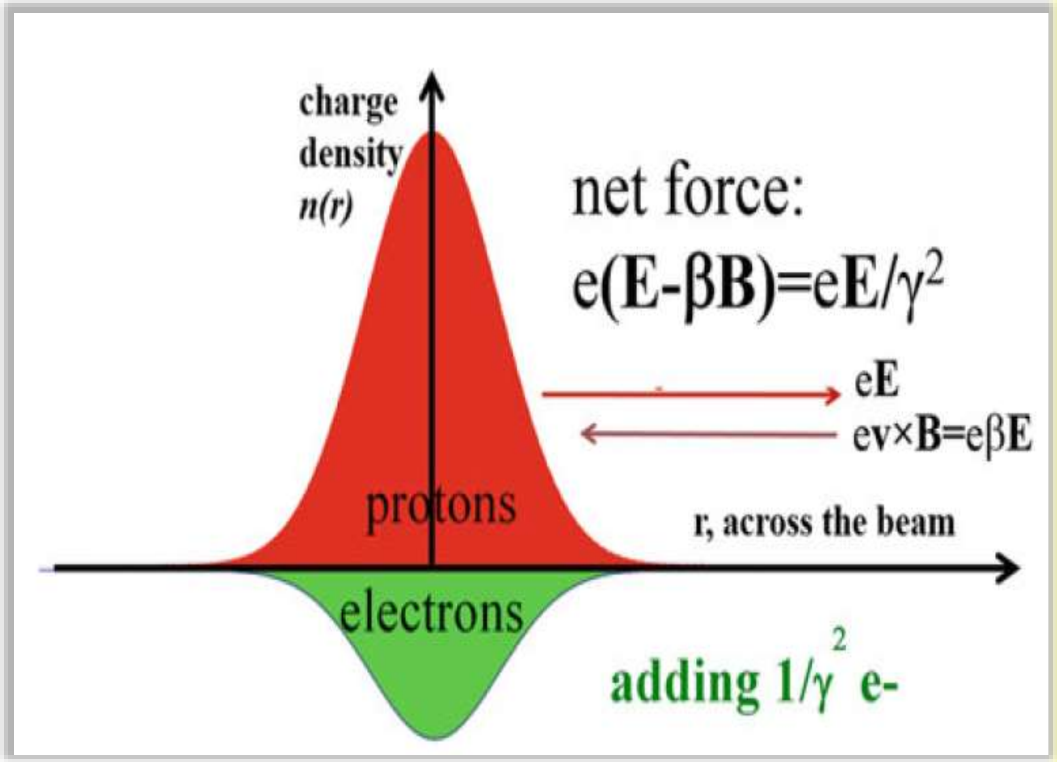
- to **compensate space-charge effects** in modern RCSs
  Burov, Foster, Shiltsev (2000), Stern et al, IPAC'18
- **hollow electron beam collimation** of protons in the HL-LHC;
  Conceptional Design Report, CERN-ACC-2014-0248 (2014)
- **long-range beam-beam compensation** as current-bearing "wires" in the HL-LHC
  *Valishev,Stancari, arXiv:1312.5006; Fartoukh et al., PRSTAB **18**, 121001 (20*
- generation of **nonlinear integrable lattices,** eg in IOTA
  Shiltsev et al, PRSTAB(1997), Nagaitsev, et al., IPAC'12; Stancari et al., IPAC'15
- to generate tune spread for **Landau damping** of instabilities before collisions in the LHC, FCC-hh (>10,000 octupoles), FNAL Recycler
  Shiltsev (2006), Shiltsev, Alexahin, Burov, Valishev PRL (2018)

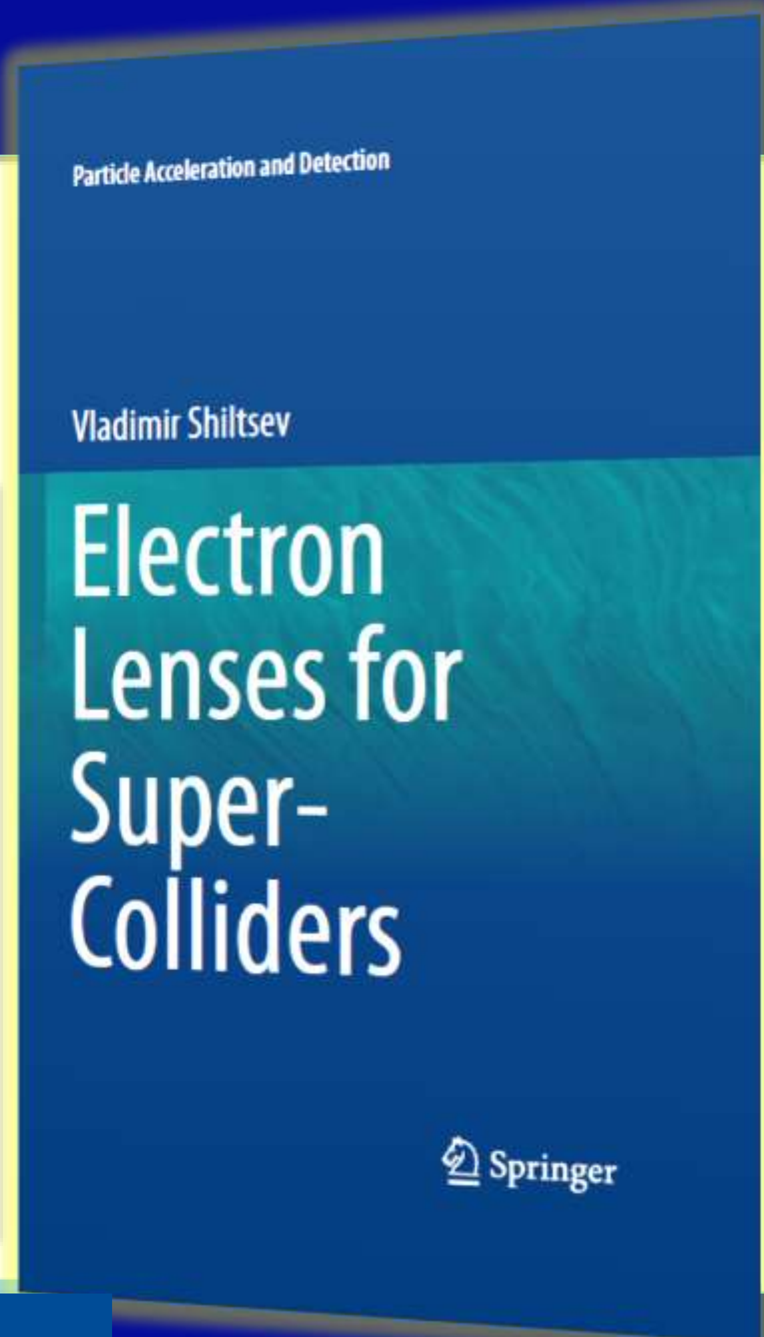
FUTURE

versatile applications depending on e-beam profile + pulsing

ABP eLens Topic #1:

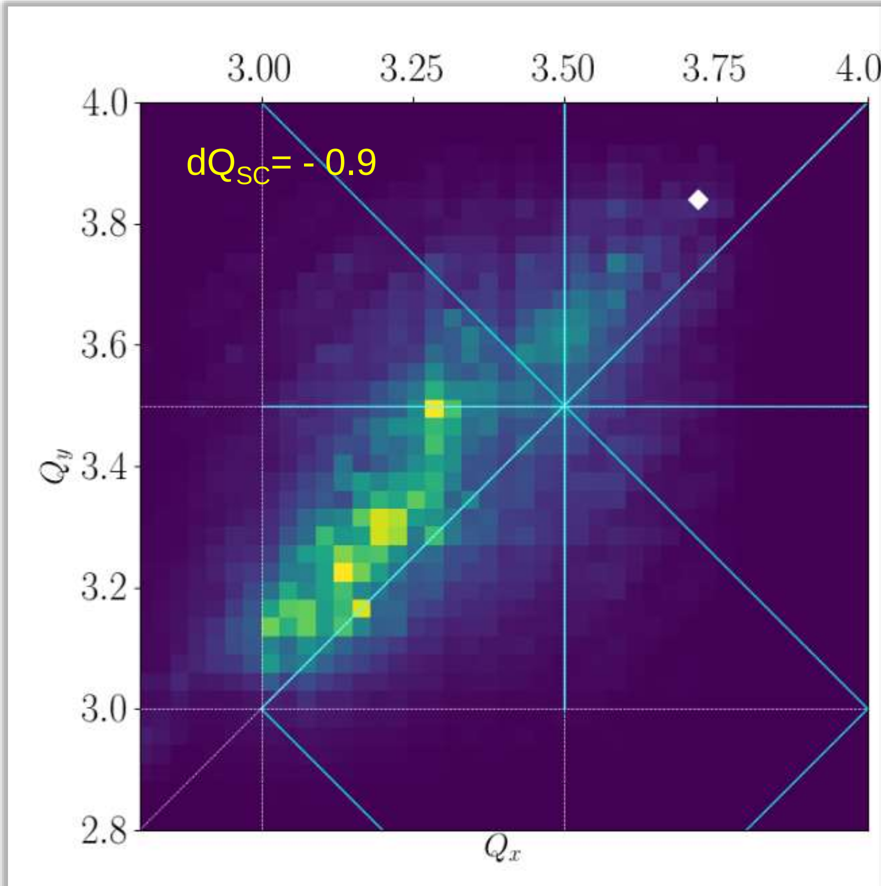
Compensation of space-charge effects by electron lenses



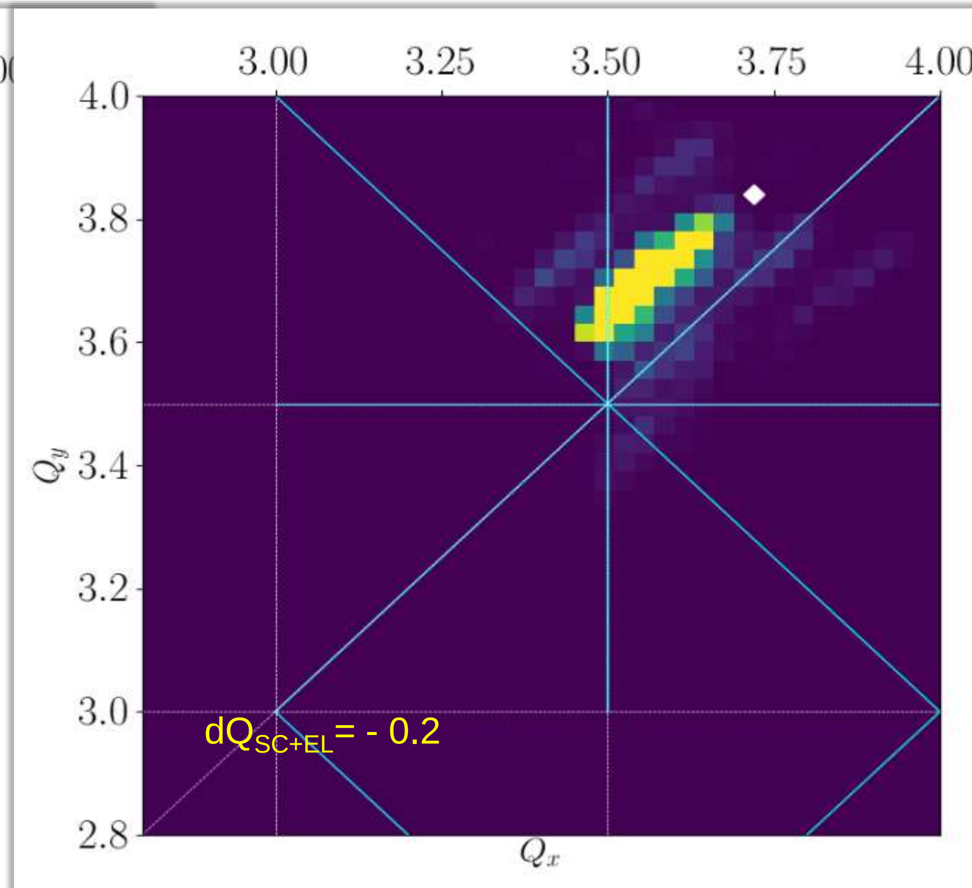


PIC simulations below - by E.Stern, et al (FNAL)

Tune Footprint dQ_{SC}=-0.9

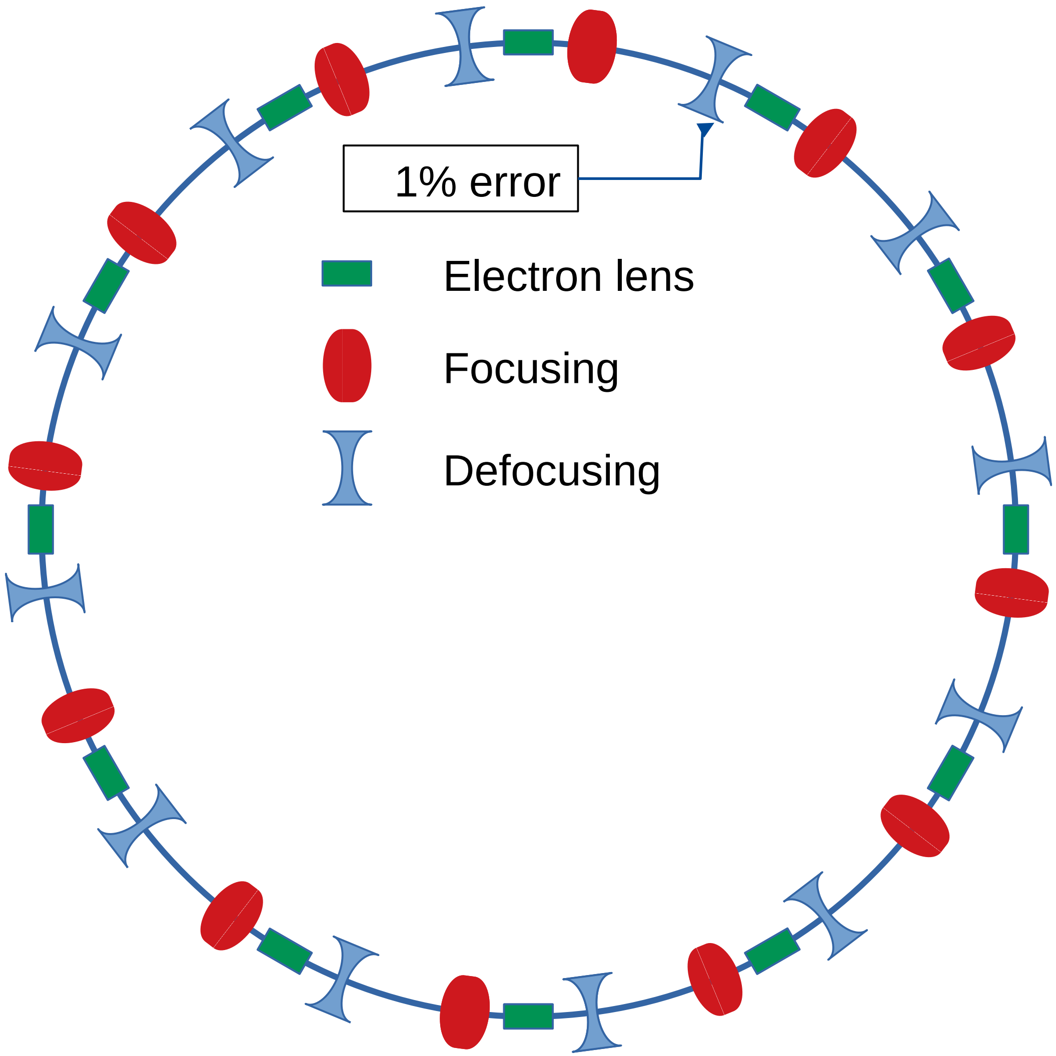


no e-lenses



~75% e-lens compensation

1000 Turns in a Ring with dQ_{SC}=-0.9

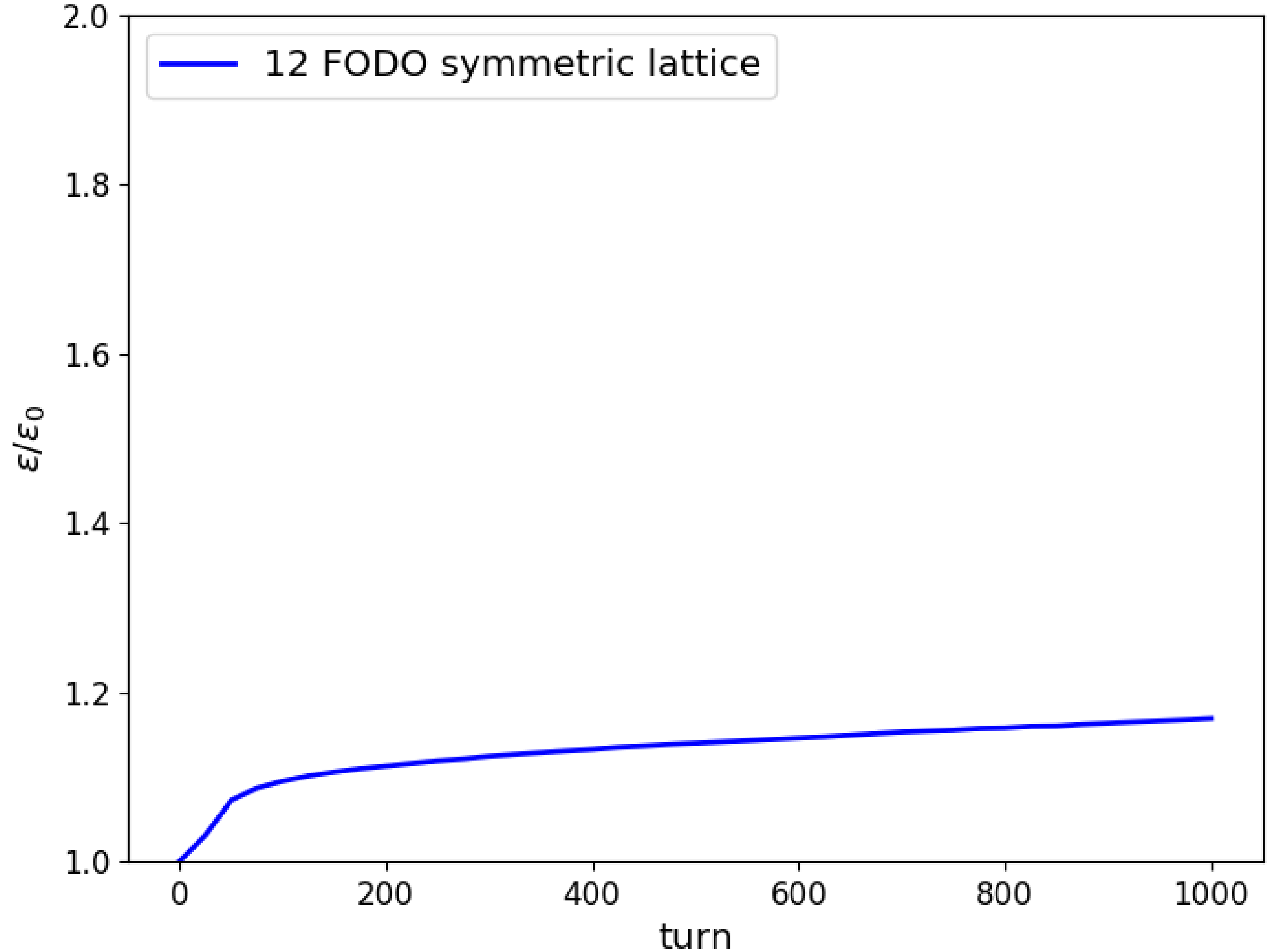


Case #1
Ideal ring

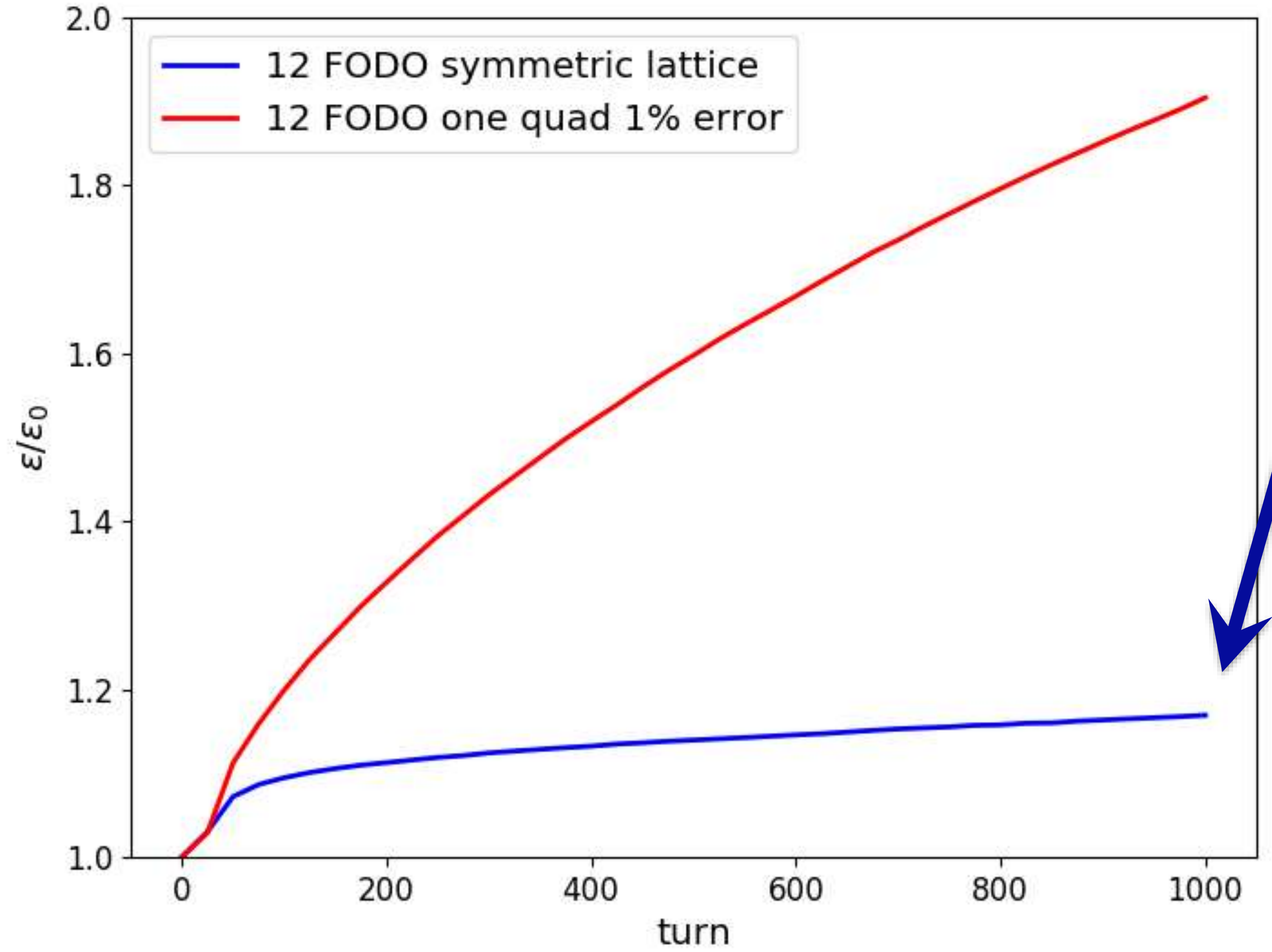
Case #2
1% error in one quad

Case #3
1% error in one quad + 12 e-Lenses

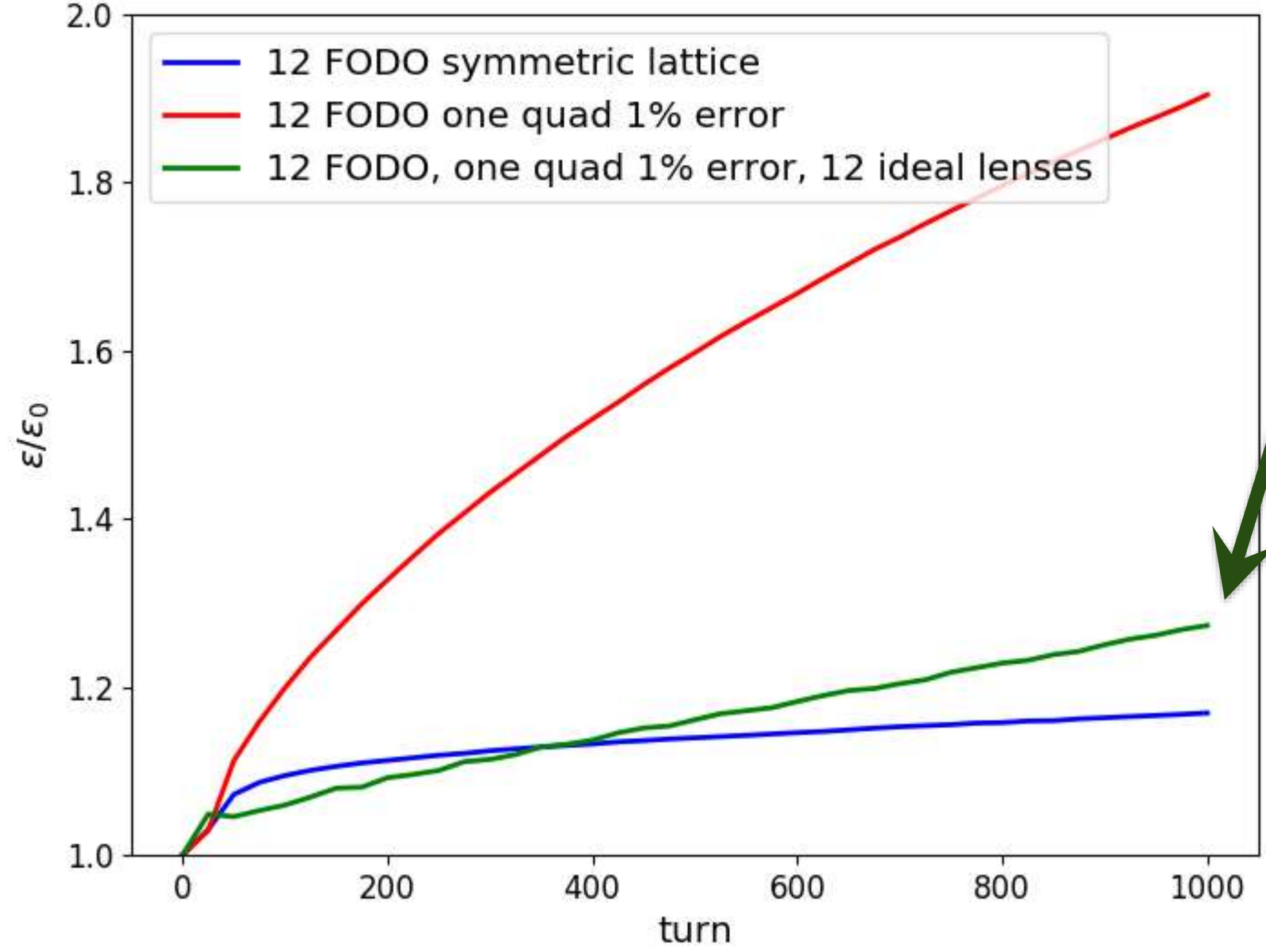
Emittance Growth – Case #1



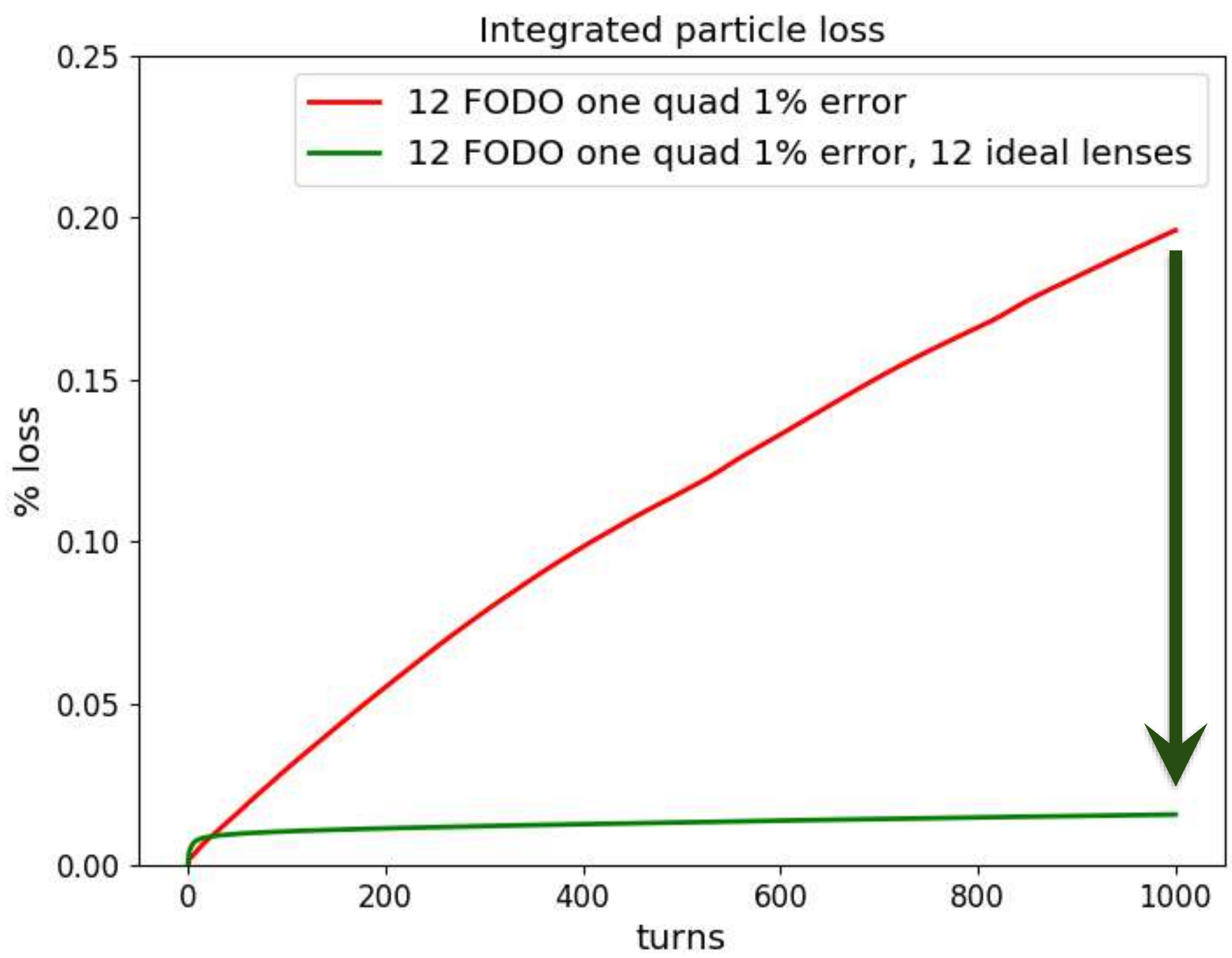
Emittance Growth – Case #2



Emittance Growth – Case #3

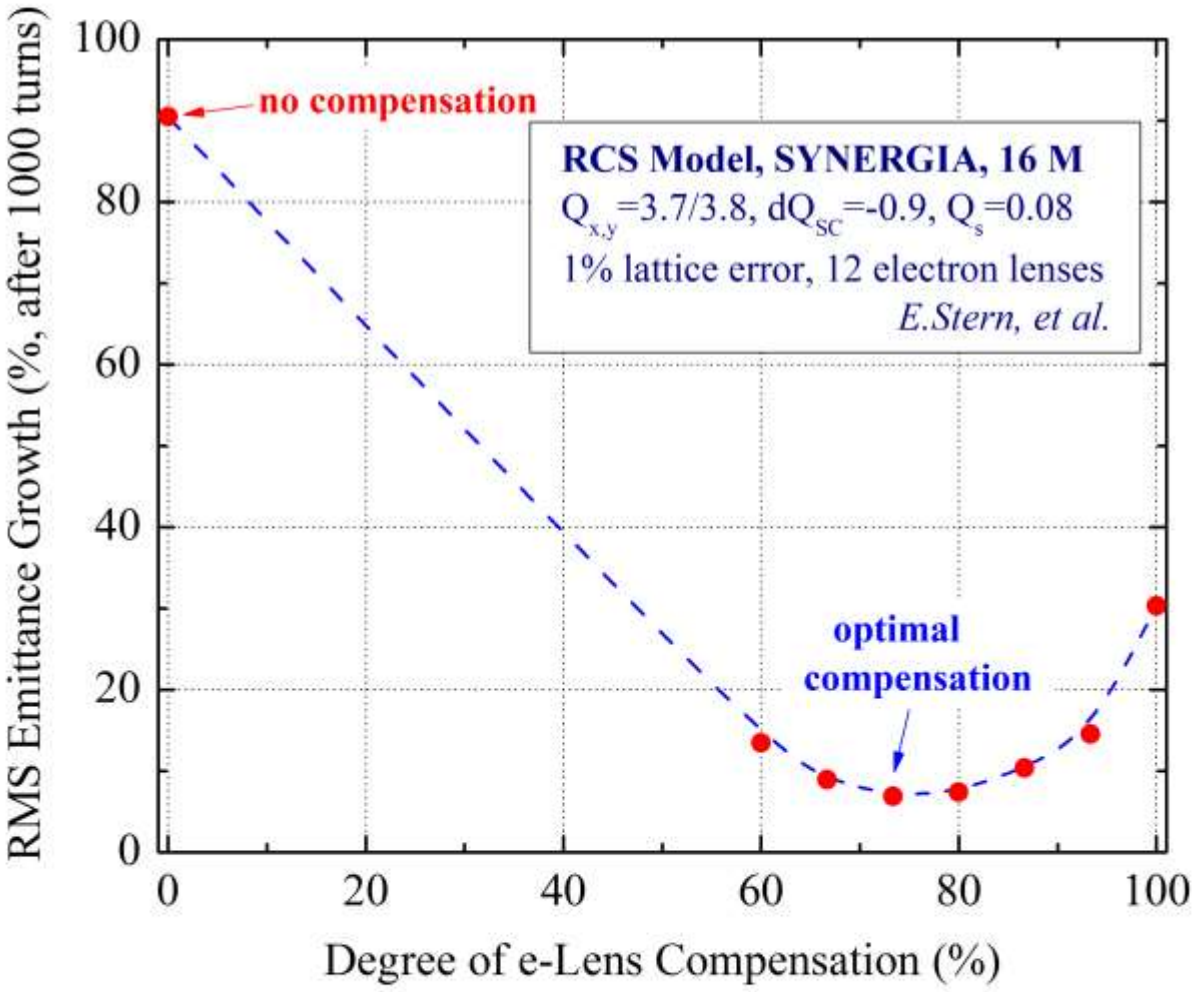


Particle Losses at 4σ – Case #2 and #3

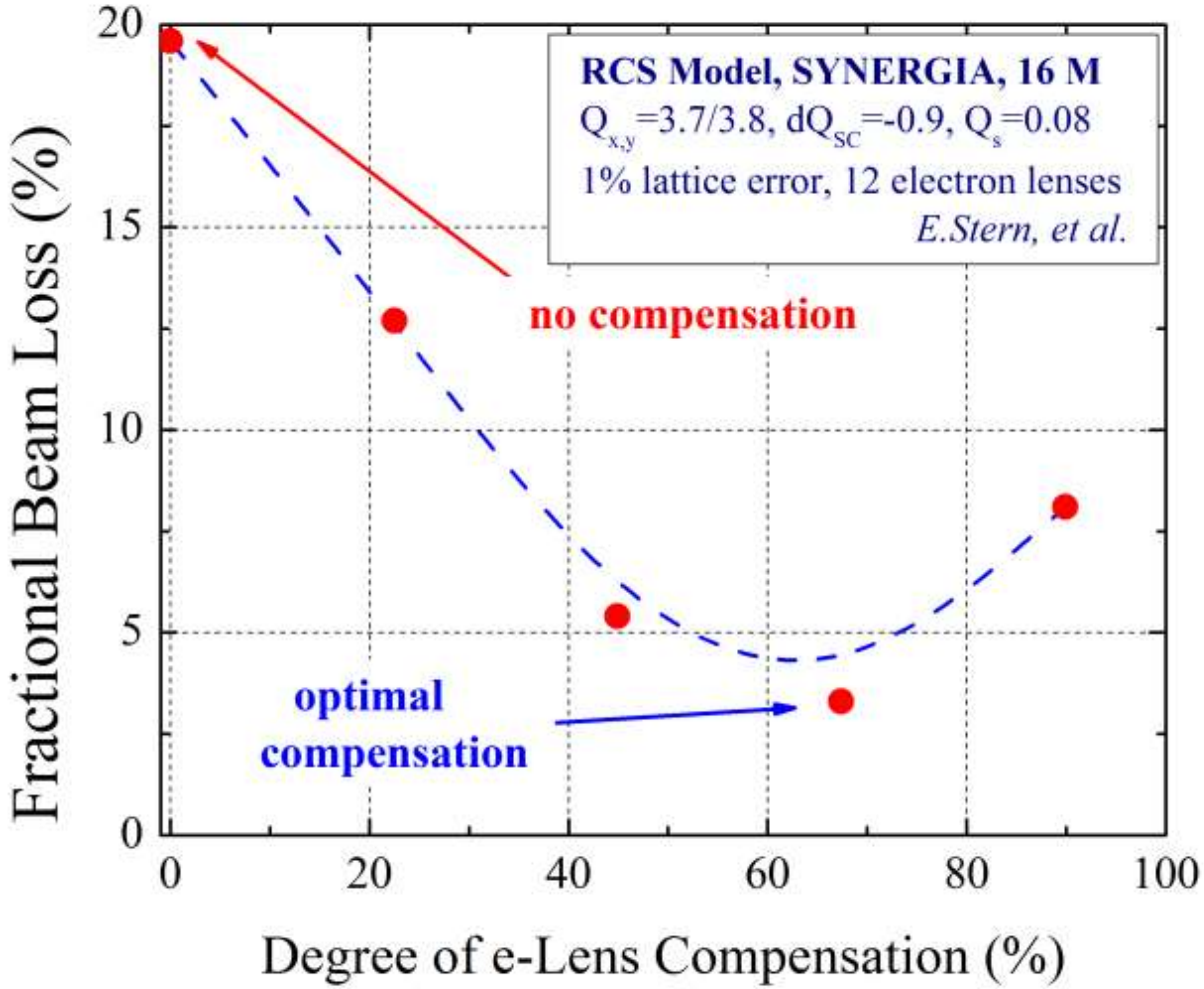


e-lenses reduce losses ~6 fold !

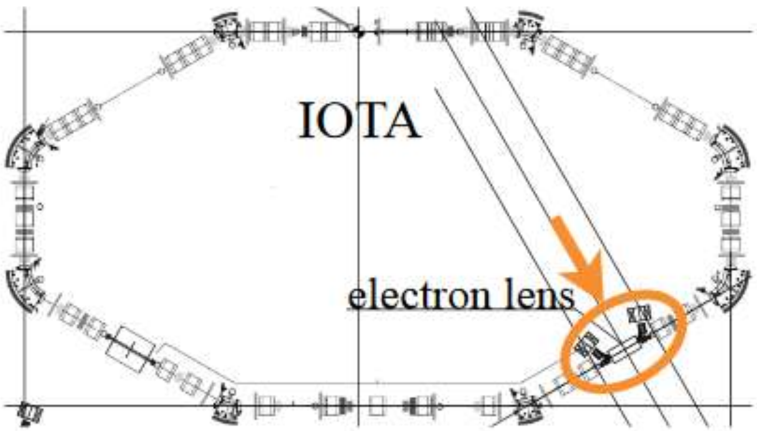
Optimal Compensation ~75% (emitt. growth)

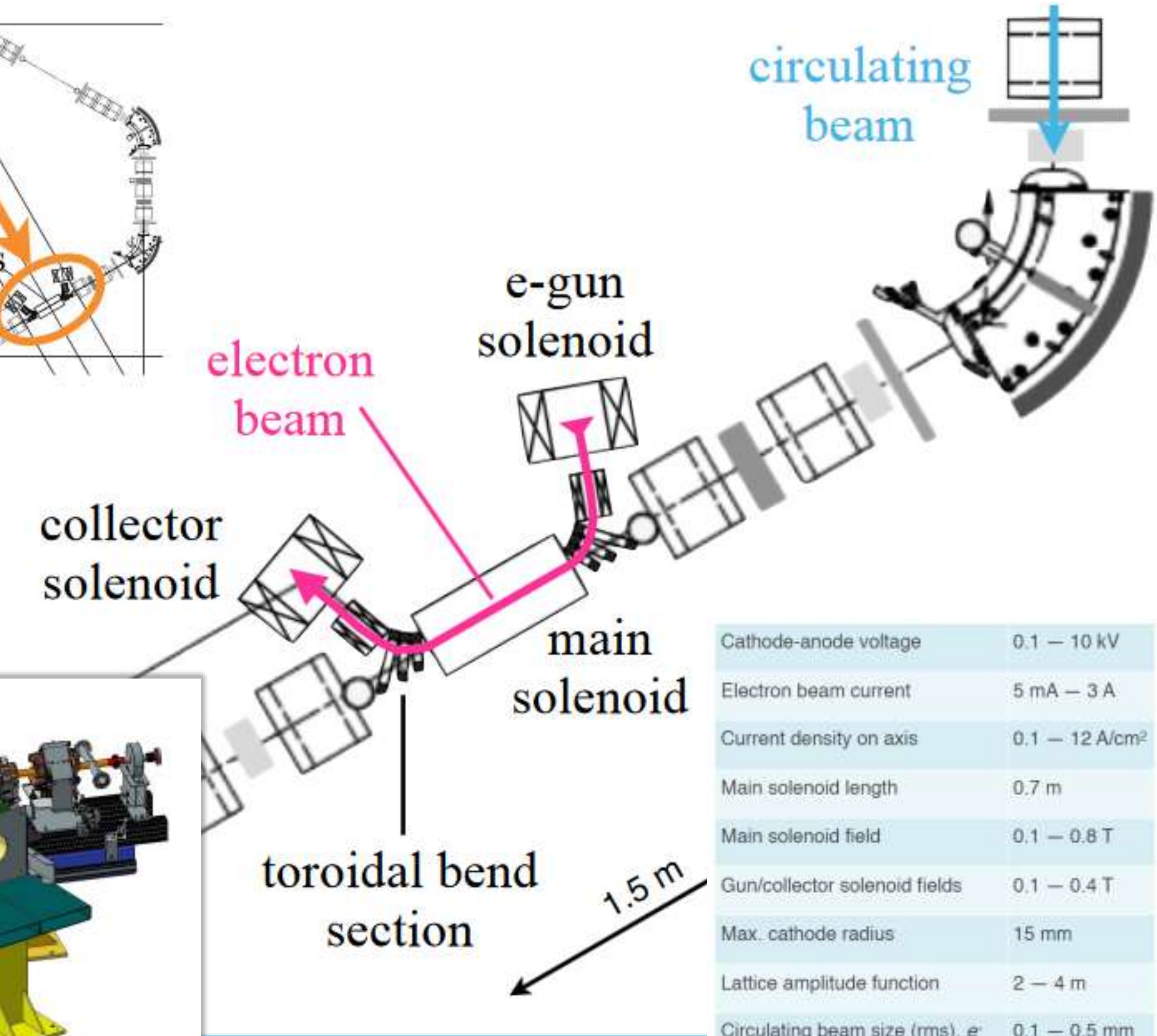


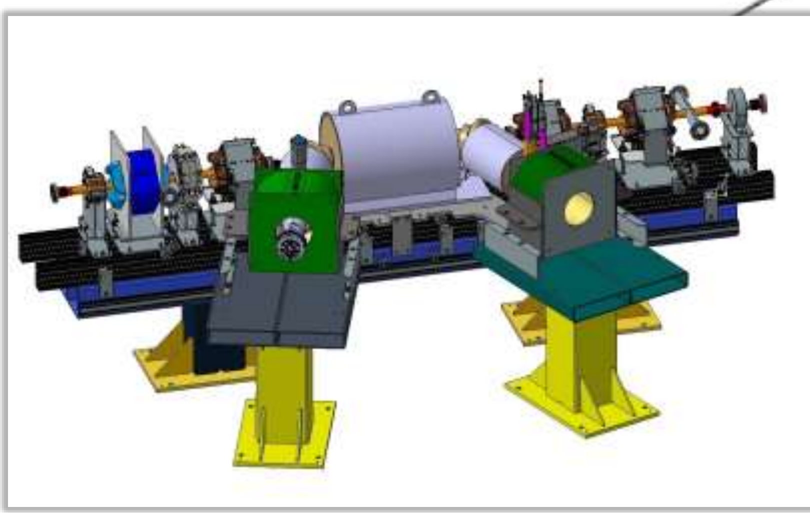
Optimal Compensation ~70% (beam losses)



Electron Lens in IOTA







Cathode-anode voltage	0.1 — 10 kV
Electron beam current	5 mA — 3 A
Current density on axis	0.1 — 12 A/cm²
Main solenoid length	0.7 m
Main solenoid field	0.1 — 0.8 T
Gun/collector solenoid fields	0.1 — 0.4 T
Max. cathode radius	15 mm
Lattice amplitude function	2 — 4 m
Circulating beam size (rms), e^-	0.1 — 0.5 mm
Circulating beam size (rms), p	1 — 5 mm

Two Add'l Important Variations

McMillan eLens

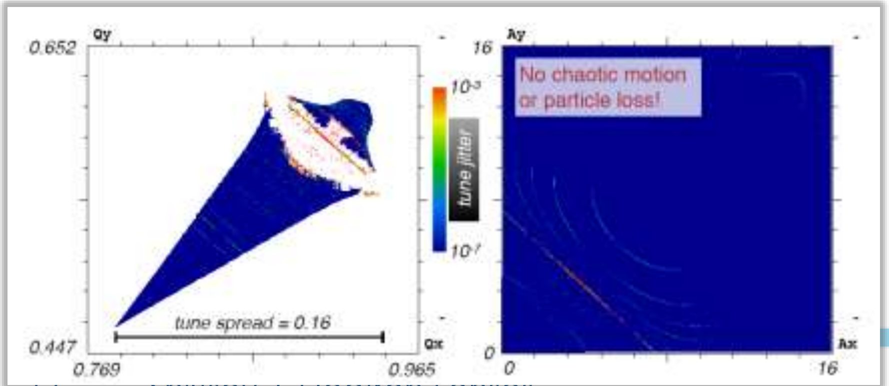
1. Axially symmetric thin kick of McMillan type

current density $j(r) = \frac{j_0 a^4}{(r^2 + a^2)^2}$

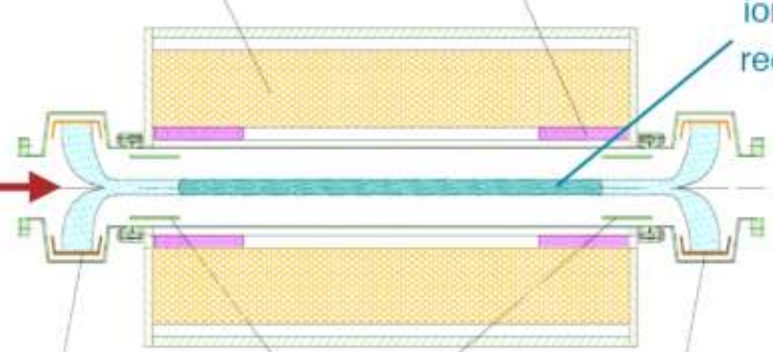
transverse kick $\theta(r) = \frac{k_e a^2 r}{r^2 + a^2}$

achievable tune spread $\sim \frac{\beta k_e}{4\pi}$

Use the electromagnetic field generate the electron distribution to provide the desired nonlinear field.



Electron Column



In strong field, ionization electrons mirror transverse profile of protons
How does the electron column evolve?

ABP *eLens* Topic #2 : Coherent Stability

PRL 119, 134802 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Landau Damping of Beam Instabilities by Electron Lenses

V. Shiltsev, Y. Alexahin, A. Burov, and A. Valishev
Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA
(Received 23 June 2017; published 27 September 2017)

Modern and future particle accelerators employ increasingly higher intensity and brighter beams of charged particles and become operationally limited by coherent beam instabilities. Usual methods to control the instabilities, such as octupole magnets, beam feedback dampers, and use of chromatic effects, become less effective and insufficient. We show that, in contrast, Lorentz forces of a low-energy, magnetically stabilized electron beam, or "electron lens," easily introduce transverse nonlinear focusing sufficient for Landau damping of transverse beam instabilities in accelerators. It is also important to note that, unlike other nonlinear elements, the electron lens provides the frequency spread mainly at the beam cor…
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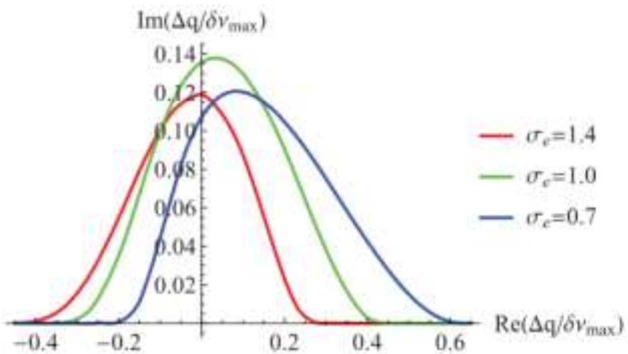

FIG. 3. Electron lens stability diagrams are presented for various electron beam sizes (noted in units of the proton beam rms size), assuming the same current density at the center.

"…For the parameters of the Future Circular Collider, a single conventional electron lens a few meters long would provide stabilization superior to *tens of thousands of superconducting octupole* magnets."

arXiv.org > physics > arXiv:1709.10020

Search or Article

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Physics > Accelerator Physics

Landau Damping with Electron Lenses in Space-Charge Dominated Beams

Yuri Alexahin, Alexey Burov, Vladimir Shiltsev

(Submitted on 28 Sep 2017)

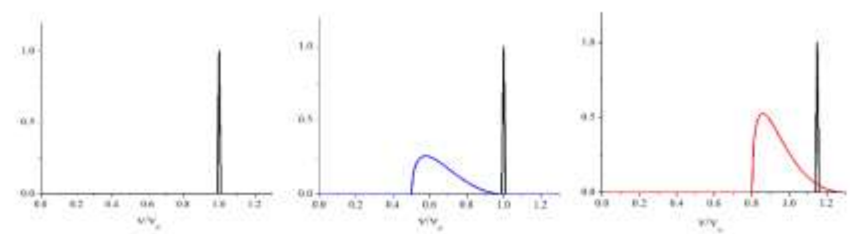


Figure 1: Illustrative dynamics of the spectra of coherent and incoherent betatron oscillations: a) left plot – in the absence of space charge forces; b) center – with strong space charge effect, but no electron lens, blue line – for incoherent frequencies, black one – for coherent; c) right - with an electron lens and in the presence of strong space charge effect, red line – for incoherent frequencies, black one – for coherent.

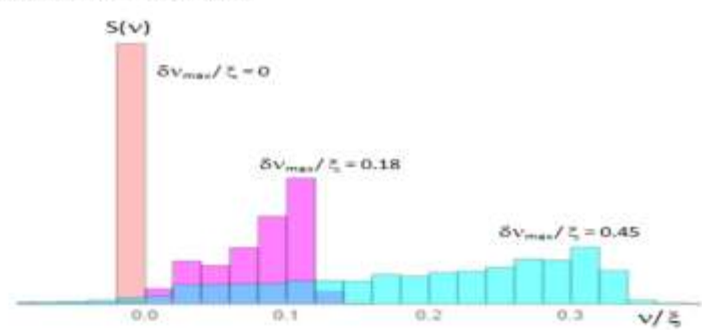
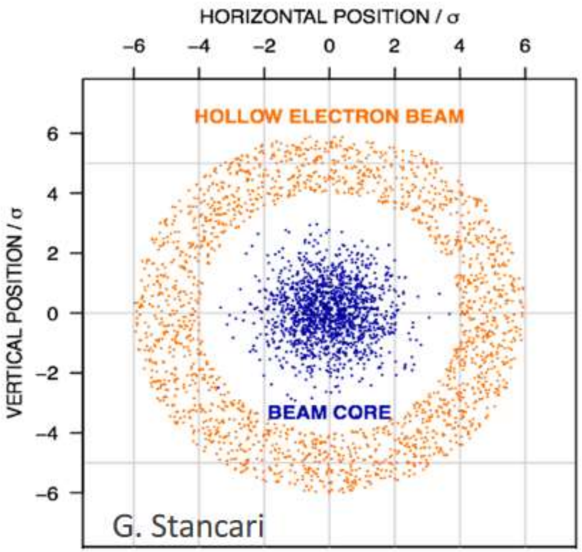


Figure 2. Spectral density of transverse oscillations in a bunch with space charge at indicated values of the maximum tuneshift due to a hollow electron lens.

A.Burov, Y. Alexahin, V.Shiltsev, A.Valishev

ABP *eLens* Topic #3 : Halo Collimation

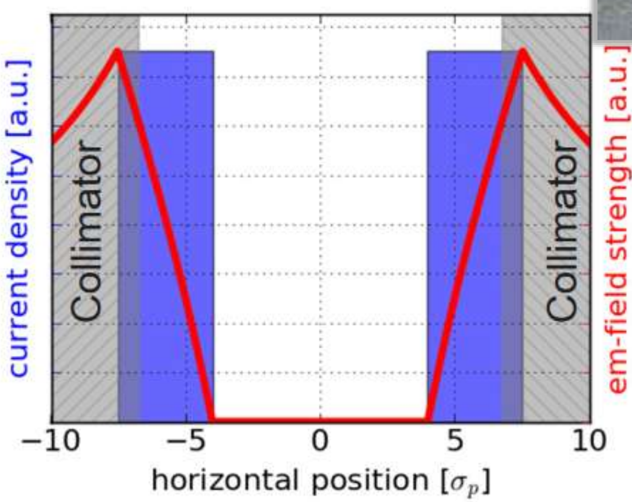
HEBC: Hollow Electron Beam Collimation : Tevatron to LHC

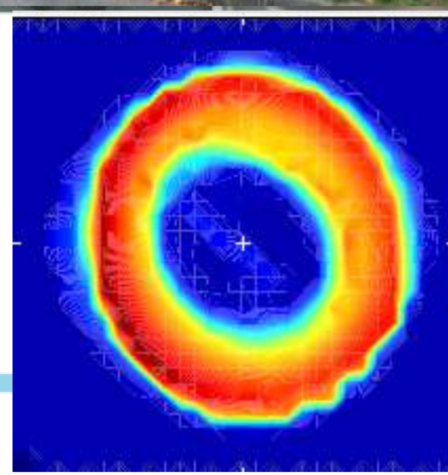


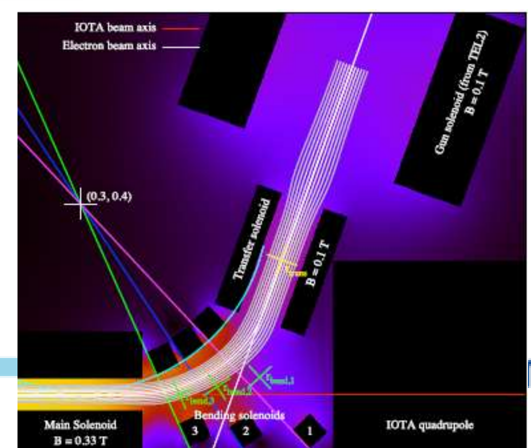
International Review on the e-lens concept readiness for integration into the HL-LHC baseline

HiLumi HL-LHC PROJECT

19-20 October 2017
CERN
Europe/Zurich timezone

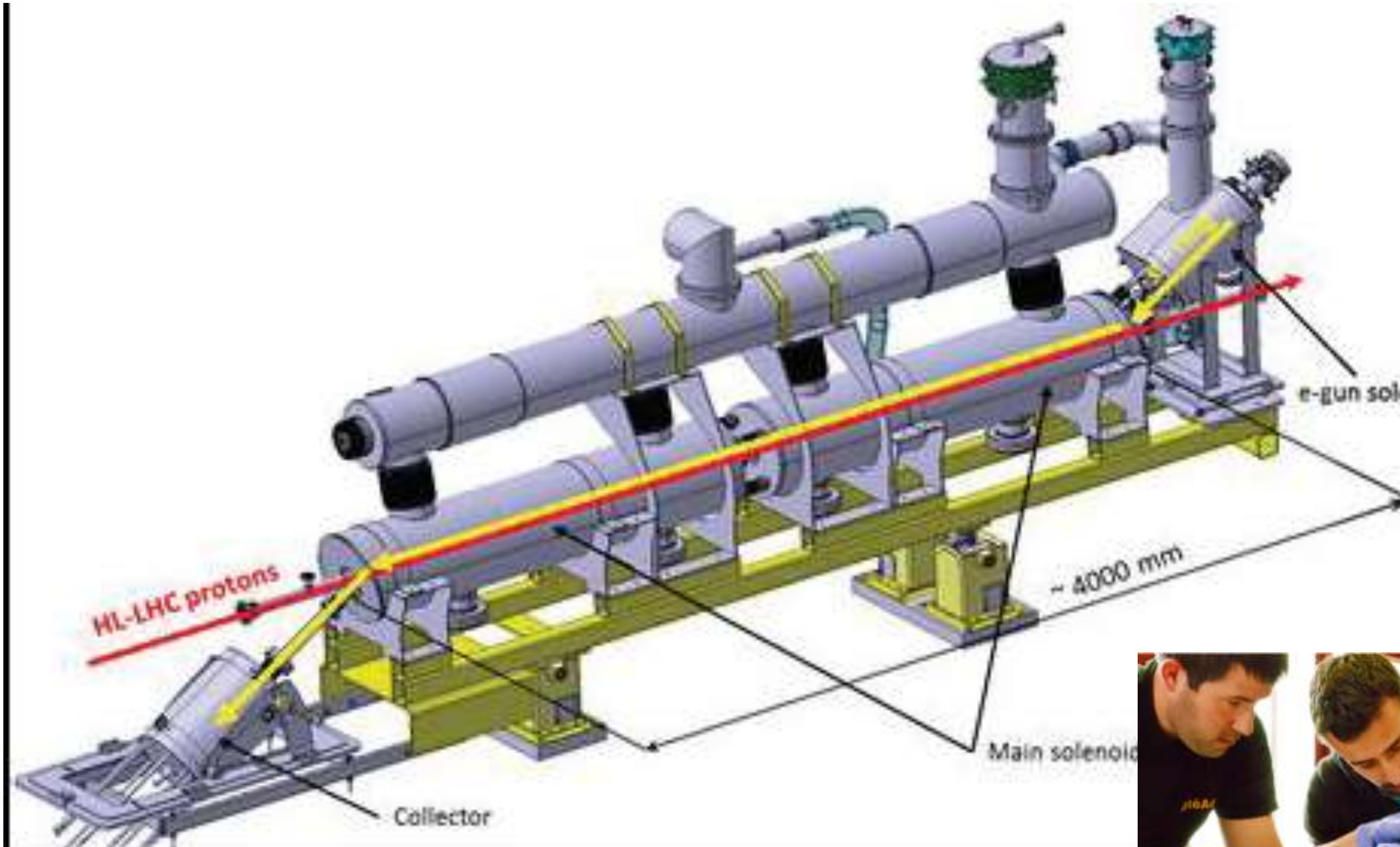






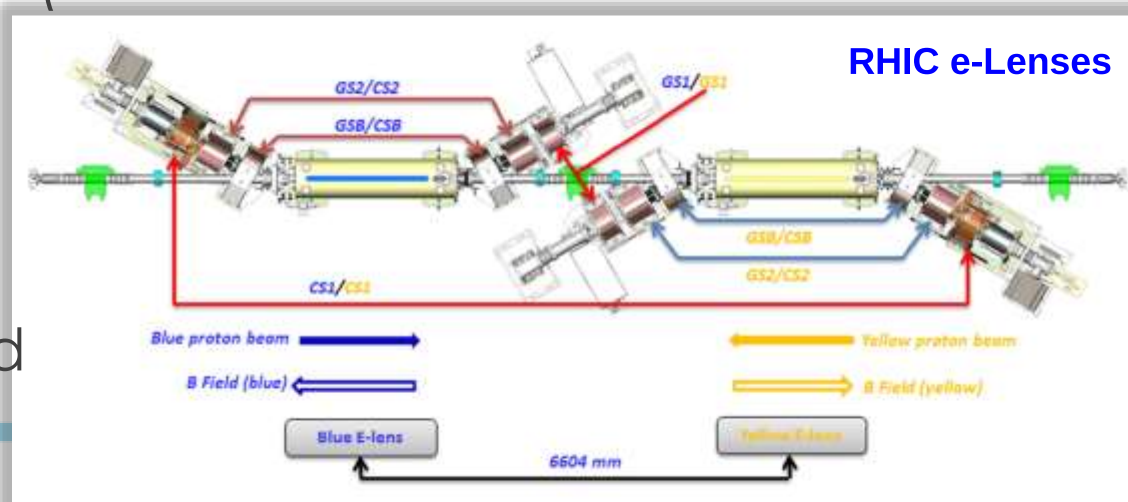
Hollow e-Lens Collimator for HL-LHC

HEBC: Hollow Electron Beam Collimation : Tevatron to LHC



Topic #4 : Beam-beam compensation

- Gaussian e-beams for head-on compensation
- Broader/smooth edge e-beams for long-range beam-beam compensation
- Found very effective in the Tevatron (LR-BBC) and RHIC (HO-BBC)
- **Can be very helpful in HL-LHC for LR-BBC:**
  - A.Valishev, S.Fartoukh, et al
  - Relatively complex (wrt to Wire LR-BBC
- **Effectiveness for future colliders (EIC and FCChh)**
  - Need to be studied

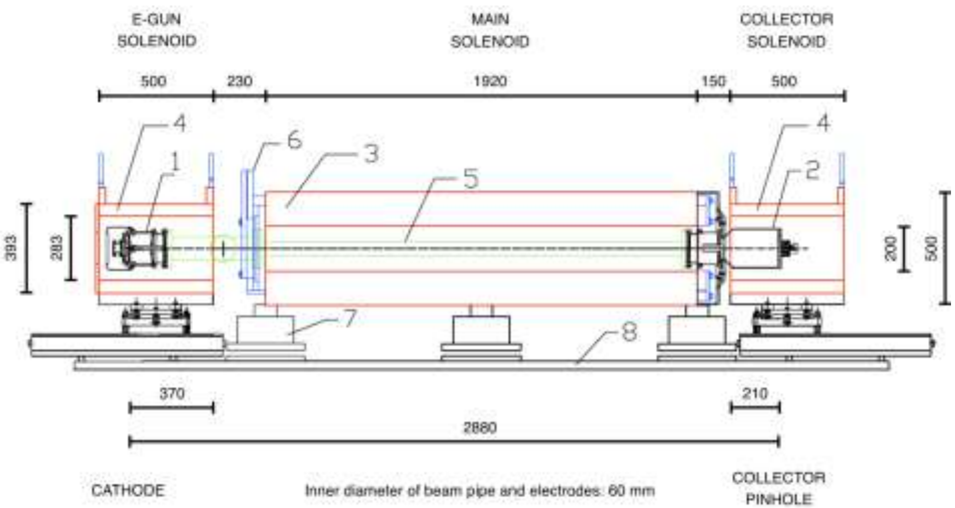


eLens challenges: How can it fail? What can go wrong with this idea?

- **Space-charge compensation risks :**
  - Physics of space-charge requires not only transverse matching as in beam-beam compensation but also longitudinal matching of e- and p+ bunches
  - Specs for the SCC are not fully explored yet
  - Specs might be very challenging for practical cost effective eLenses
- **E-lenses for Landau damping risk :**
  - Physics and technological risks are limited
- **Hollow eLens Collimation risk:**
  - Physics risks is limited
  - Technological risks in generation of the proper beam profile, problem-free bending sections, and proper time modulation
- **eLens beam-beam compensation risks :**
  - Physics and technological risks are limited
  - Specs might be very challenging for practical cost effective eLenses (if high A*m are needed for high current colliders)

Facilities: Fermilab and CERN test stands … Upgrades

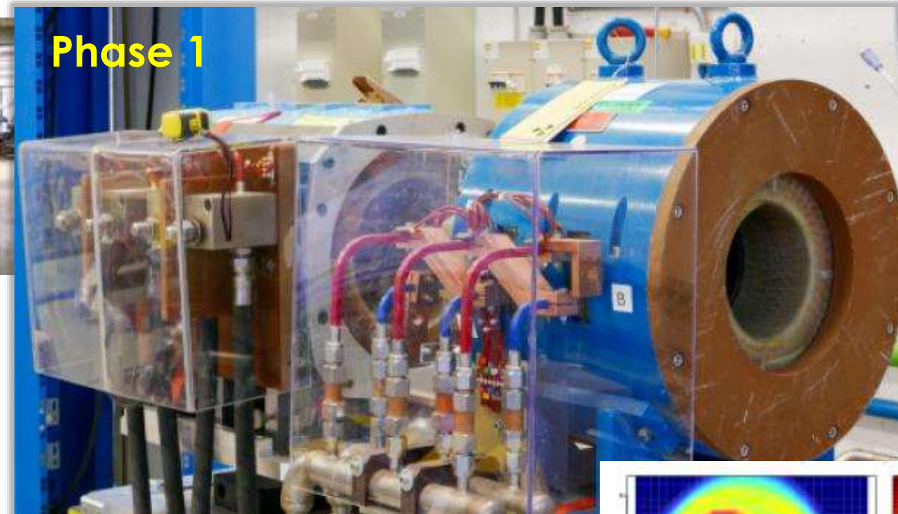
Fermilab elens test stand

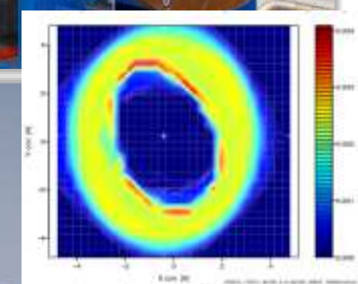


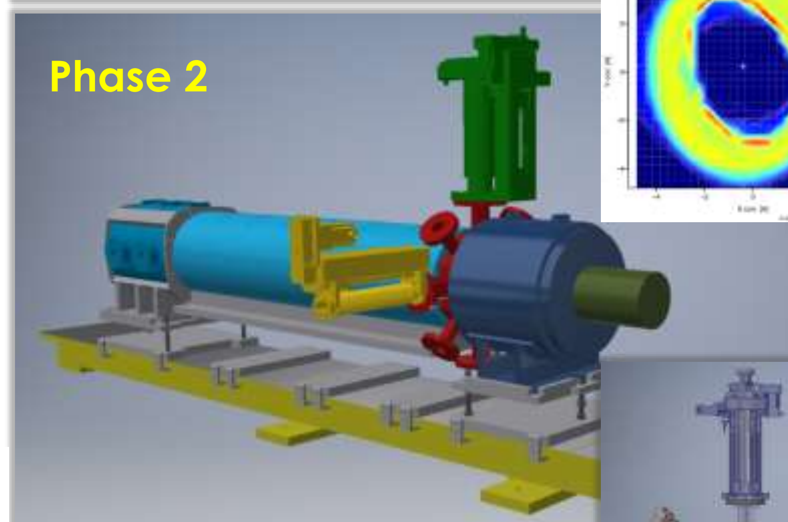
Operational, up to 10 kV, 8υs x 1Hz pulses (or higher at lower current). Used to test Tevatron and CERN guns, will be used for testing guns for space-charge compensation at IOTA ring. Could be used to test HF modulators.

<u>Upgrades needed:</u> for higher intensity, faster modulators and new profile diagnostics

CERN electron lens test stand







Diagnostics Box →

Electron Lenses and the *GARD ABP Grand challenges*

- **Grand challenge #1 (beam intensity):** How do we increase beam intensities by orders of magnitude?
  - eLens Space-Charge Compensation can lead to factor 2-5 in intensity
  - eLens Landau damping can keep narrow beams stable x10-100
- **Grand challenge #2 (beam quality):** How do we increase beam phase-space density by orders of magnitude, towards quantum degeneracy limit?
  - eLens Landau damping can keep superbright beams stable x10-100
  - eLens Beam-beam/SC compensation can allow x2-5 in ξ and dQ_{SC}
- **Grand challenge #3 (beam control):** How do we control the beam distribution down to the level of individual particles?
  - eLens Halo collimation can control losses of superbright beams
  - eLens in McMillan form can control beam distribution and losses
- **Grand Challenge #4 (beam prediction):** How do we develop predictive "virtual particle accelerators"?
  - eLens SC and BBC require arguably the most predictive modeling tools

Describe an approximate timeline in relation to grand challenges: #1 – 10-15 yrs; #2 – 10-20 yrs; #3 – 5-10 yrs; #4 – 5-10 yrs

Electron Lenses and the *GARD ABP Missions*

- **Advance physics of accelerators and beams to enable future accelerators.**
  - Substantially expand intensity/power reach of future multi-MW RCSs via space-charge loss control and luminosity reach of future EF hadron colliders via beam-beam, syability and halo control
- **Develop conventional and advanced accelerator concepts and tools to disrupt existing costly technology paradigms in coordination with other GARD thrusts.**
  - eLens SC compensation can allow (less expensive) RCS options for multi-mW beams; inexpensive luminosity increase tools
- **Guide and help to fully exploit science at the GARD beam facilities and operational accelerators.**
  - Vigorous eLens program in IOTA; HL-LHC e-beam collimation greatly helps
- **Educate and train future accelerator physicists.**
  - eLenses offer unmatched variety for development of existing and new concepts for operational and future accelerators, rich collaborations

Electron Lenses and *HEP-Specific Missions*

- **Intensity frontier**
  - Space-charge compensation can be a game-changer for next generation cost efficient multi-MW machines for neutrino physics **(eg PIP-III)**
- **Energy frontier: hadron colliders**
  - Halo collimation, Landau damping and beam-beam compensation have be a game-changer for next generation hh-Colliders **(HL-, HE-LHC, FCChh)**
- **Energy frontier: lepton colliders**
  - Space-charge compensation will advance proton drivers for muon colliders **(MC)**
- **Accelerators for physics beyond colliders and Standard Model**
  - SC-compensation for cost efficient multi-MW beams

Electron Lenses : *Synergies and Connections*

- **To other GARD thrusts :**
  - High Field Magnets : SC solenoids for eLens beamsize compression
  - Targetry and Sources :
  - AAC : PIC plasma simulations (Space-charge, Beam-beam, Landau damping)
- **To other SC offices :**
  - BES : space-charge compensation in protons beams for spallation neutron sources
  - Nuclear Physics : beam-beam and space-charge compensation in EIC; synergy with e-cooling
  - FES : high sield solenoids; PIC plasma simulations (Space-charge, Beam-beam, Landau damping); physics of electron columns/traps

Collaborations: Who is working on this now?

- **Fermilab:**
  - Exp/HW/Test stands: G.Stancari, V.Shiltsev, B.Cathey, et al
  - Modeling/Simulations: E.Stern, A.Valishev, A.Burov, et al
  - Collaborating Universities / Labs:
    - LBNL (C.Mitchell, et al), NIU (B.Freemire), Korea (M.Chung, C.S.Park), RadiaSoft (J.Edelen, C.Hall); Finland (Lapland U.)
- **BNL:** W.Fischer, X.Gu, et al
- **CERN:**
  - Exp/HW/Test stands: S.Radealli, D.Perini, et al
  - Modeling/Simulations: A.Rossi, S. Sadovich, et al
  - Collaborating Universities/Labs
    - BINP (Novosibirsk): A.Levichev, D.Nikiforov, et al
    - Germany: J.Wagner (Frankfurt), et al
    - China: W.Shao, et al

ABP *eLens* R&D: Milestones (draft)

- **Space-charge compensation :**
  - IOTA eLens installed **2021-2022**
  - SCC experimental studies **2022-2028**
  - Mod/Sim's on eLens SCC **2020-2028**
  - Decision on PIP-III eLens SCC **2028**
  - Pre-project & Constr'n SCC-PIP-III **ca 2035**
- **Electron Lenses for Colliders :**
  - Landau Damping exp's RHIC and IOTA **2020-2024**
  - HL-LHC HEBC development **2020-2022**
  - HL-LHC HEBC installed **2024-2025**
  - Design/Simulation work complete for FCC-hh Landau damping eL, HEBC and beam-beam **2032**
  - FCC-hh electron lenses prototypes **2040**

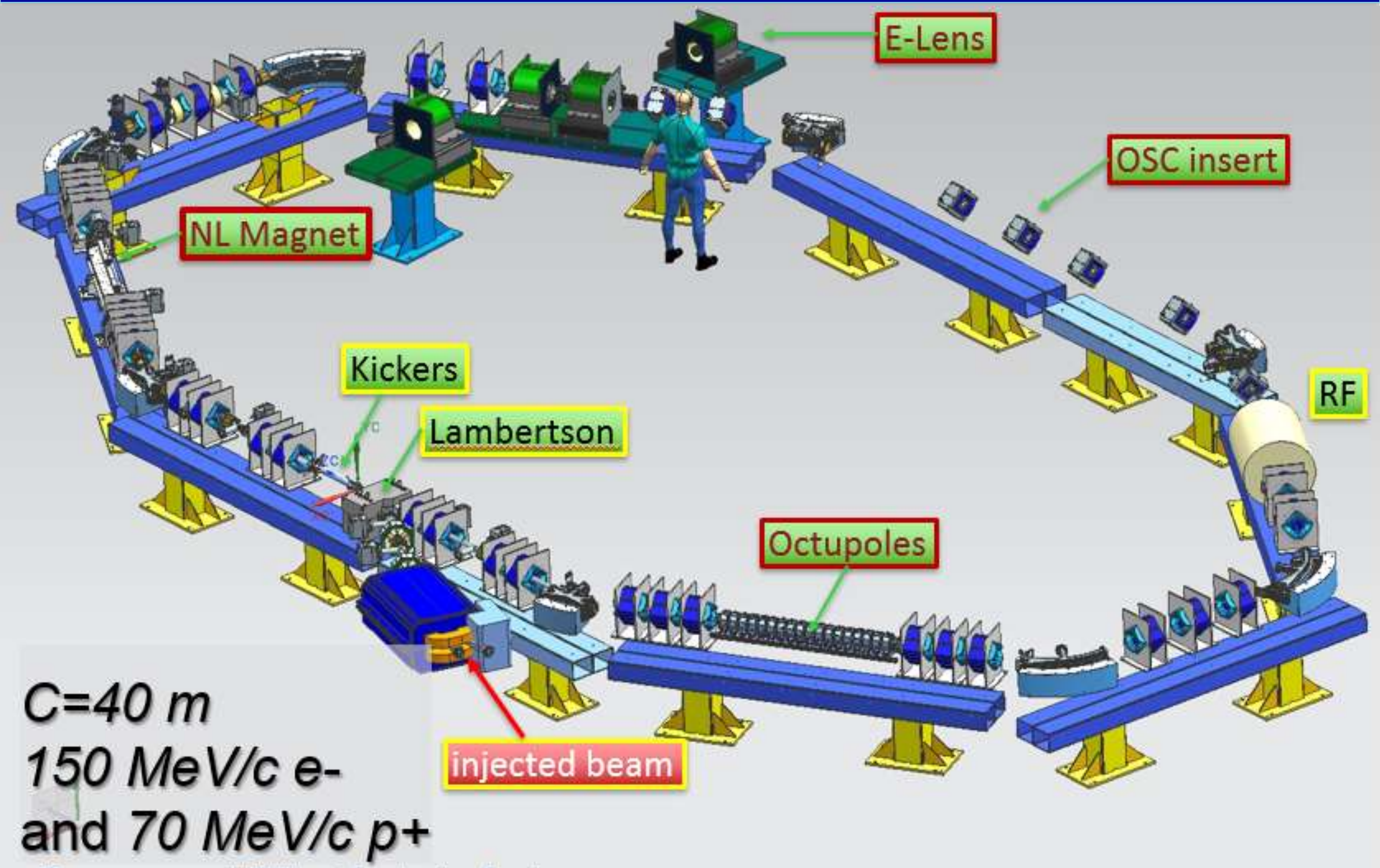
Electron Lenses R&D : Possible Roadmap

	2020	2025	2030	2035	2040
ELECTRON LENS SPACE CHARGE COMPENSATION					
MODELING/SIMUL's	dQ_{SC}=-1 specs IOTA SCC Experiment	IOTA Analysis	Multi-MW RCS CDR		
IOTA EXPERIMENTS	Build / Install	McMillan / Compensation	2nd Lens? e-column? Double dQ_{SC} ?		
DESIGN/PROTOTYPING	IOTA			Multi-MW RCS EL Design / Prototyping	
ELECTRON LENSES FOR ENERGY FRONTIER COLLIDERS					
HALO COLLIMATION	RHIC PoP exp HL-LHC e-Collimator build & install		HL-LHC e-Collimator commissioning & studies	FCC e-coll. design/ prototyping	
BEAM-BEAM COMPENS.	RHIC head-on compensation	HL-LHC LR/HO Modeling	HL-LHC BBC studies ?		FCC-hh BBC design
LANDAU DAMPING		IOTA studies	HL-LHC Modeling	HL-LHC studies?	FCC-hh design
ELECTRON LENS TECHNOLOGY AND TEST STANDS					
FERMILAB TEST STAND	HL-LHC IOTA		Multi-MW RCS & FCC EL Components Prototyping → Test Stand		

In general, electron lens R&D is of direct relevance to the US HEP priorities for intensity and energy frontier science outlined by 2014 P5 and those foreseen in the 2021 Snowmass report. Electron lenses combine practical feasibility and potential "blue-sky" high-impact.

Back up slides

IOTA: *Integrable Optics Test Accelerator*



Speaker guidelines

- Emphasize broad forward-looking research topics other than your specific R&D program
- Focus on your view of future challenges and methods to address those challenges.
- My abstracts:
  - "Electron Lenses for Landau damping".

Developments of higher and higher brightness beams call for new methods of the beam stability control. Traditional ways to ensure Landau damping by nonlinear elements, such as eg octupoles, become less efficient for unprecedentedly narrow beams. Electron lenses are considered as an extremely useful and versatile tool for stability control which seems to be free of traditional caveats of reduced dynamic aperture.

  - "Space-charge compensation".

A 60-years old problem of space-charge limit affects all types of modern hadron accelerators. There are several approaches including active space-charge compensation with electron lenses, electron columns or other means of externally controlled neutralization. It needs to be explored theoretically and experimentally whether indeed the space-charge parameters (figure of merit such as tune shift or tune suppression) can be increased by substantial factors - thus paving the way to new revolutionary accelerators.

Slides 1 – 4: Research idea/proposal

- Please address the following:

- Describe the science/R&D that you are proposing to do.
- Briefly describe present "state of the art" – you presentation should include this!

- What is the desirable outcome? What are the potential impacts?
- How does it fit into the GARD ABP missions (see above)?
- How can it fail? What can go wrong with this idea?
- Is it testable? What facility?

Slide 5: Grand challenges

- Which Grand Challenges (see above) is this proposal/idea addressing?
- Describe an approximate timeline in relation to grand challenges

Slide 6: HEP missions

- How is your proposed research related to the HEP-specific missions?
  - Intensity frontier
  - Energy frontier: hadron
  - Energy frontier: lepton
  - Accelerators for physics beyond colliders and Standard Model
- “Blue-sky” with high-impact and relevance to HEP.

Slide 7-8: Synergies

- Describe potential synergies and connections to other GARD thrusts and other SC offices (BES, NP, QIS, FES, etc)

Slides 9-10: Timeline (aka the Roadmap)

- Describe the proposed timeline and associated milestones

Electron Lenses R&D : Approx. Timeline (10 yrs)

Year	2020	2025	2030

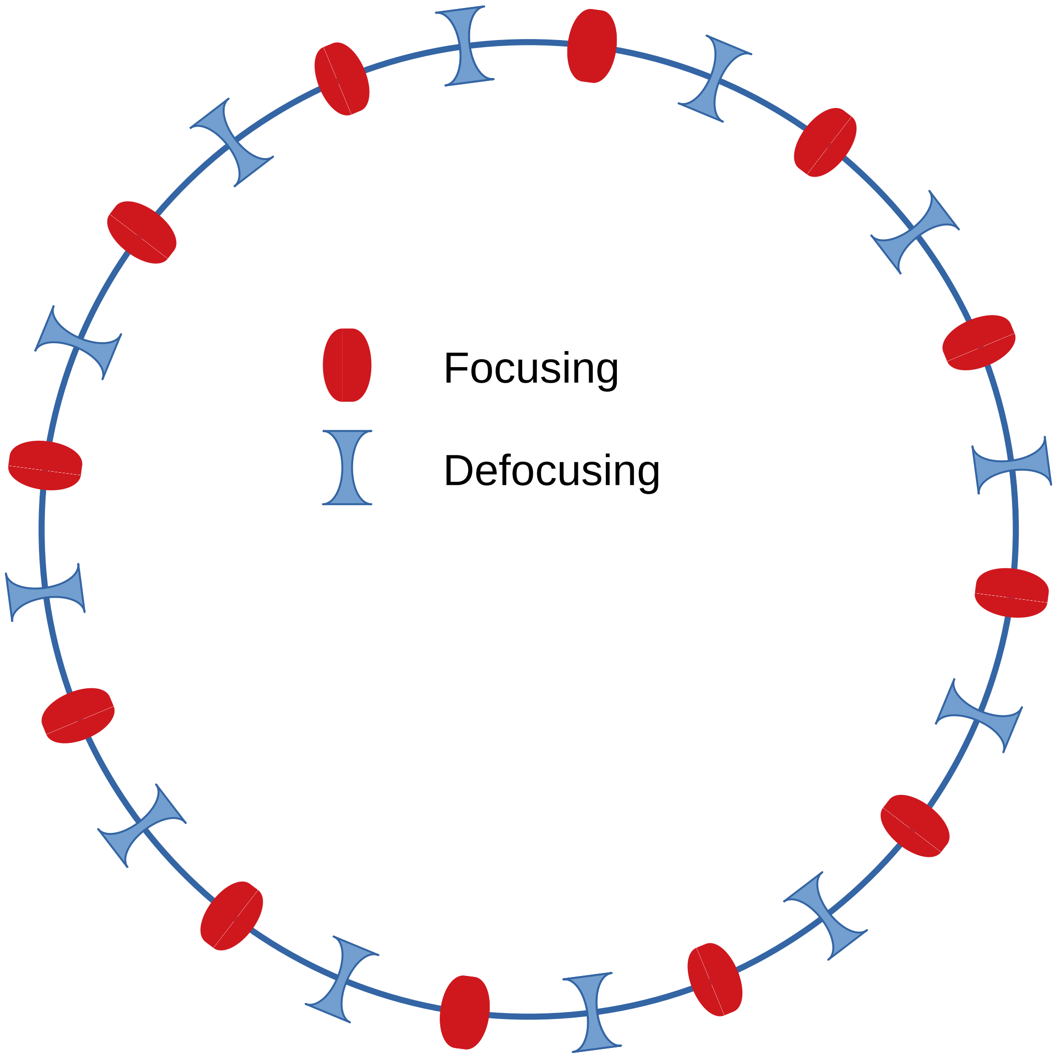
2020 2025 2030

E-Lenses R&D : Approx. Timeline (next 10 yrs)

Year	2030	2035	2040

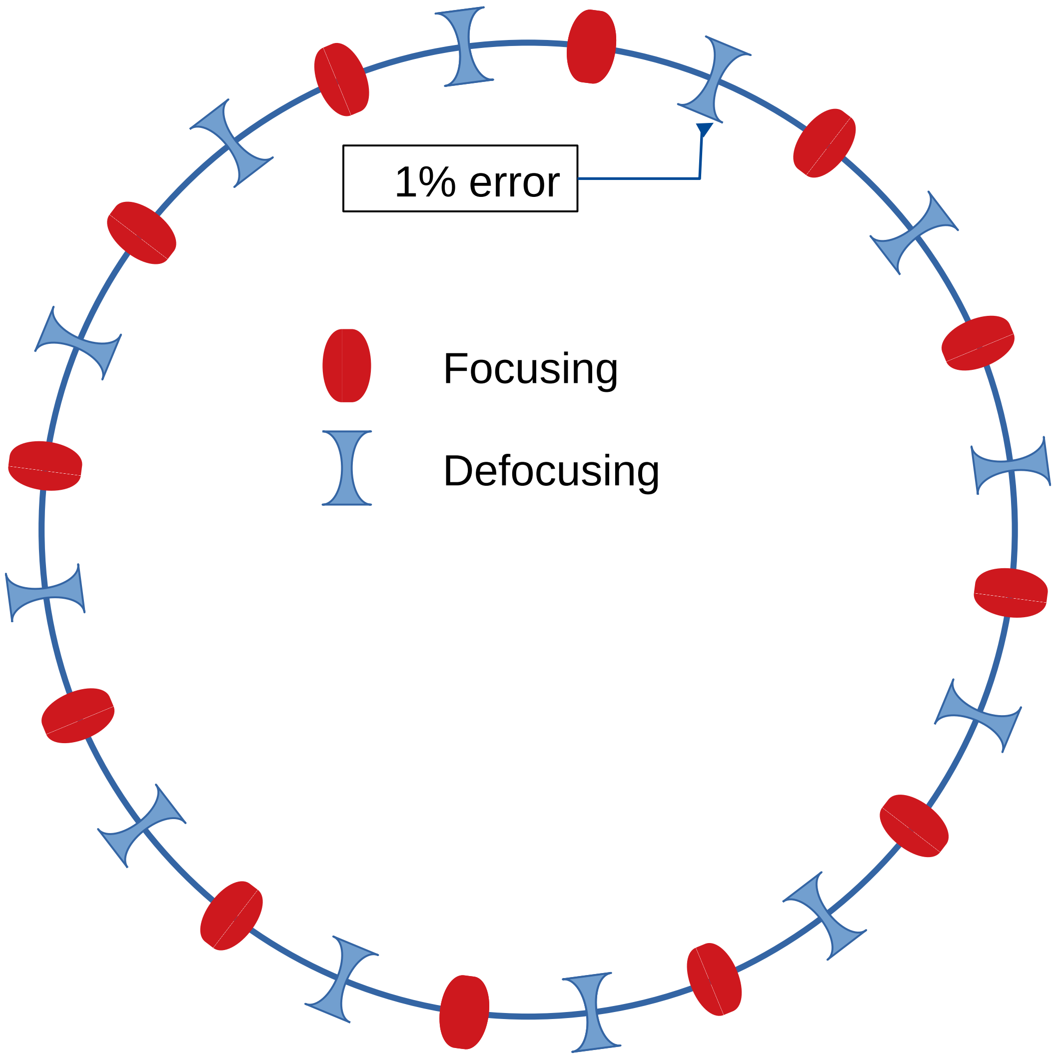
2030	2035	2040

1000 Turns in a Ring with dQ_{SC}=-0.9



Case #1

1000 Turns in a Ring with dQ_{SC}=-0.9



Case #2